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Markert, Frank

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Frank Markert[1]

METHODS SUPPORTING FIRE RISK ASSESSMENT AND MANAGEMENT

Abstract: Fire risks may be described using a probabilistic approach to take account for the uncertainties in the description of scenarios. This is different from a pure deterministic approach using models that predict precise outcomes based on a set of defined input data.. There are different philosophies to describe fire risks as the frequentist approach relaying on failure statistics of e.g. components or the Bayesian Believe Networks. More recently approaches to better describe the dynamic behavior of systems are being developed. These models are used to establish the essential information for risk informed decision support. They are further useful to design the proper fire risk management for the respective systems that goes beyond the risk assessment and includes maintenance of safety barriers.

Keywords: Risk Assessment , risk management, fault tree, event tree, dynamic model

[1] Associate Professor, Technical University of Denmark, Department of Civil Engineering, Section for Building Design, Brovej 118, Dk-2800 Kongens Lyngby, fram@byg.dtu.dk

1. INTRODUCTION

1.1. Objective and scope of lecture

Performance based fire safety engineering is a valuable method to assess fire risks. It is a scientific based alternative to prescriptive assessments. The performance based approach is relying on a number of deterministic and probabilistic models such as fire plume models, ignition models, fire spread models, evacuation time models, event trees, fault trees, Bayesian networks to predict the required and available safe egress times. These are ranging from engineering correlations and simplified models to CFD models and Monte Carlo type calculations. All types are important: for the assessment of very detailed scenarious the CFD approach will provide the best results, but on the cost of calculation and interpretation time. The simplified models allow to predict a great number of scenarious that can be extended to Monte Carlo type of modelling to establish a good overview on the important scenarious as they are fast calculating but on the cost of details. to predict systems and systems safety

2. FRAMEWORK FOR BUILDING FIRE SAFETY

2.1. The IRCC- hierachy

The IRCC has developped an 8 tier approach for a fire engineering strategy as reported by Meacham (Meacham 2010), decribed below. It describes a hierachy of fire safety measurese to protect people and structures in case of a fire event. It emphases the protection of people in accordance with the use of the specific building.

- tier 1 Goal (safety): provide an environment reasonbly free from injury and death
    - Buildings shall provide occupants with a reasonable level of safety from natural and technological hazards
- tier 2 Functional statement (fire / life safety)
    - Provide appropriate measures to protect occupants not intimate with the initial materials burning from the negative effects of unwanted fire.
- tier 3 Operative requirement
    - Means of egress shall be designed such that occupants not intimate with the initial materials burning are provided with adequate time to reach a place of safety without being unreasonably exposed to untenable conditions resulting from the fire.
- tier 4 Performance / Risk groups
    - Performance/ Risk groups (e.g. PGI, PGII, PGIII, PGIV). These regard: a) Primary uses(s) of the building, general building characteristics, etc.; b) Importance of the building; c) Occupant risk charcteristics as associated with the primary use(s) of the building; d) Type of hazard event and magnitude of hazard event the building and occupants are expected to withstand (design loads)
- tier 5 Performance levels

    - Performance levels (Levels of tolerable impact (e.g. mild, moderate, high , severe)
- tier 6 Performance criteria
- tier 7 & 8 Solution and verification verification methods
    - Gas temperature; b) Thermal radiation; c) Smoke density; d) Smoke level above floor; e) CO level; f) Structural failure temperature
    - Herunder to establish: a) Test methods; b) Installation standards; c) Analytical or computational models; d) Design guides

This is in accordance with the ISO definition of "Fire Safety Engineering" (see (Dansk Standard 2012)), as e.g. addapted in (National Research Council Canada; International Code Council (USA); New Zealand. Dept. of Building and Housing; Australian Building Codes Board 2005) (link to guidelines):

"*The application of engineering priciples, rules and expert judgement based on a scientific appreciation of the fire phenomena, of the effects of fire, and the reaction and behaviour of people, in order to:*

1. *save life, protect property and preserve the environment and heritage;*
2. *quantify the hazards and risk of fire and its effects;*
3. *evaluate analytically the optimum protective and preventative measures necessary to limit, within prescribed levels, the consequences of fire*"

In order to apply fire engineering, it is necessary to understand the many aspects of building fires that are invetigated within the area of fire science. Herunder, it is essential to establish knowlegde about the ignition mechanisms of the different materials and fire develop including fire spread scenarious and fire chemistry. This provides the basis to predict smoke spread and toxic fire effluent concentrations important to know for the rescue of people. This knowledge is also important to determine the reaction to fire of structures. Furthermore, the knowledge how people respond in case of a fire, to the alarms and the process of evacuation is important. This is within fire science established using fire dynamics theory; using deterministic and probabilistic fir e behaviour and effects modellingt; as well as human behaviour and toxic effects modelling. Such knowledge is implemented into various tools to conduct performance based fire engineering in practice.

3. A GENERAL ACCIDENT MODEL

Real fire accident scenarious are often complex. In order to systemize and to support development of fire scenarious an accident model is presented. This accident model is based on the uncontrolled flow of energy (UFOE) concept and is described by (Rasmussen & Grønberg n.d.). The concept is considering the term energy very broadly embracing energy forms as for instance heat, heat radiation, mechanical energy and other forms of energy.

More broadly the concept additionally includes material flows and toxic substances under the term „energy“ (see Figure 1).

In the normal state, the energy is controlled and any process applying the energy is regarded as safe. It can be said that the energy is confined by the process equipment essential to drive the process. For achieving a higher safety level, additional safety functions may be implementet that are only activated in case of an accidental event. The location where the energy is confined is called the hazard source. In case of an accident the confinement is violated. It is called a Loss of Confinemnet (LoC) situation. On LoC the energy is released resulting in an UFOE situation. The UFOE may expose vulnerable objects. These maybe people, property or environment. This model is valid for fire scenarious as well as industrial accidents.

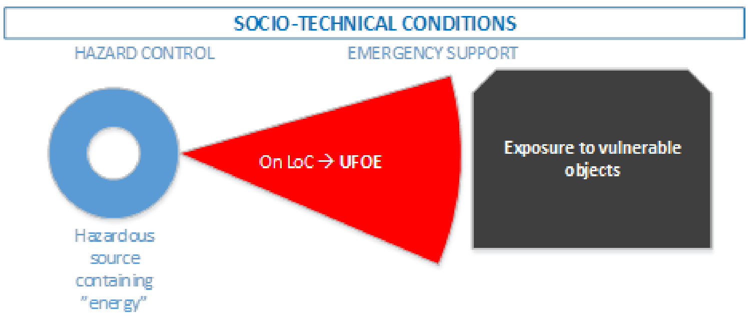

Figure 1 UFOE model

Under a UFOE situation emergency support is needed. The model regards six universal emergency measures to prevent or mitigate exposures of the vulnerable objects. These are:

1. move vulnerable objects: evacuate plant stuff, evacuate neighbors, stop traffic to ares, remove valuable objects
2. modify energy: water curtain, sprinkling
3. redirect flow: lead water form fire fighting away from sensitive areas, collect water from fire fighting (portable spill basins), build interimistic dams
4. control source: extinguish fire, cover leak
5. encapsulate moving energy: cover with foam
6. establish negative source: lead spill to sewer, add chemical agents to bind dangerous substances

4. THE IMPORTANCE OF THE SOCIO-TECHNICAL SYSTEM

The UFOE model shown in Figure 1 describes any accident within a socio-technical system. This is not only true for the emergency reponce as described above, but it is also true for controlling the hazardous source. Any accident is the result of a number of steps leading to the overall consequence of a specific accident. Besides technical errors also human and organisational factors are part of an accident. This is illustrated by (Svedung & Rasmussen 2002), where the critical event is also dependent on the organisational interactions withithe socio-technological sytem as shown in Figure 2. Here the LoC or critical event is modelled using a bow-tie representation together with the interrelation of staff, their management and the whole company. The national safety policy is defined and influenced by regulaters and branch associations and on the highest level by the government deciding on the necessary laws for regulation of e.g. building and infrastructure fire safety.

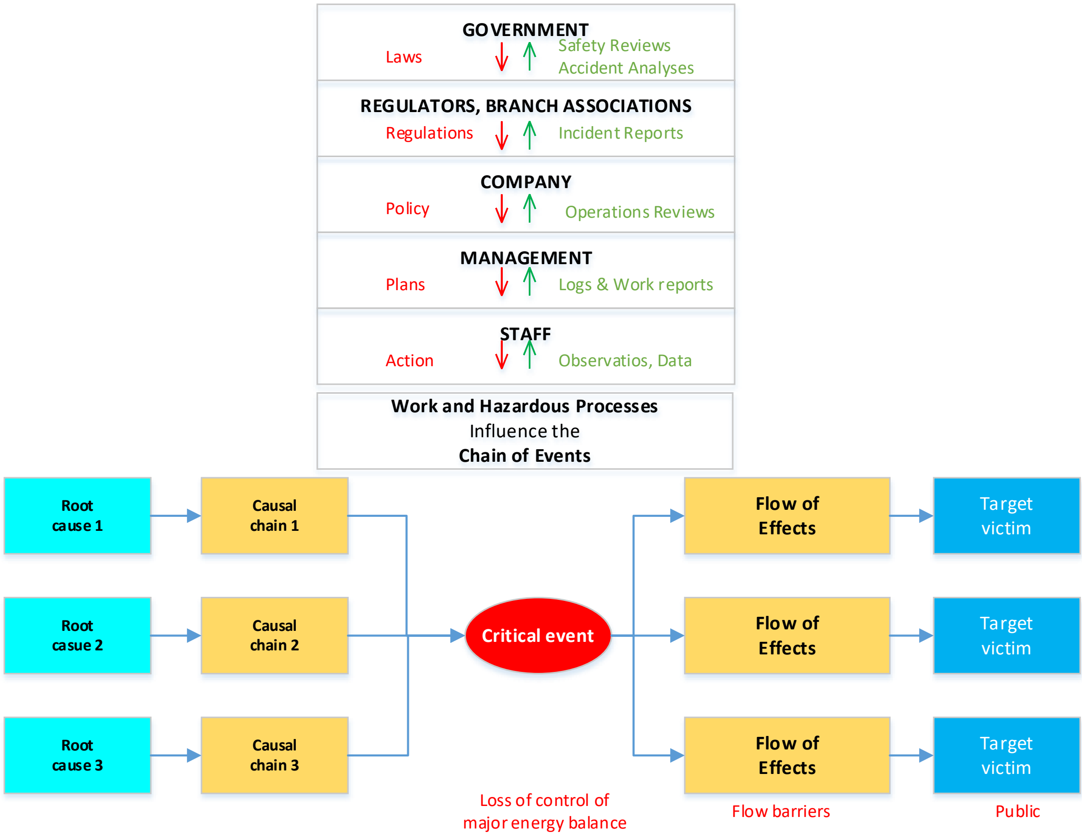

Figure 2 Model by Rasmussen and Svedung socio-technical model of system operations (e.g. (Svedung & Rasmussen 2002)*)*

5. PERFORMANCE BASED FIRE SAFETY ASSESSMENT

In order to implement the above some practical tools and approaches are to be used within the performance based approach. The main goal is to evacuate and to rescue people from any building. The basic approach to fullfill this is the ASET / RSET approach, which stands for "Available safe egress time" and "Required safe egress time", respectively. The ASET depends on the actual fire scenario, while the RSET describes the time that is reasonable needed to leave the fire location to a rescued area inside a large building and/or in front af a building. This is described as the ratio of ASET vs RSET and a value below 1 is deemed to be a safe situation, while values close to and above 1 are describing unsafe situations that may cause loss of life and injuries of people. (see Figure 6)

The RSET is the result of the inherent system safety of each building, as it is measuring and calculating the evacuation time on basis of the length of the evacuation paths, the established safety features as the detection and alarming systems, fire sprinkling, fire doors and other means. It takes into account a risk that parts of these safety functions are faulty and my not work in case of the fire situation. It could be that the location of the starting fire is preventing a single escape route and /or that some of the safety barriers such as the fire doors or detection & alarm systems do not function.

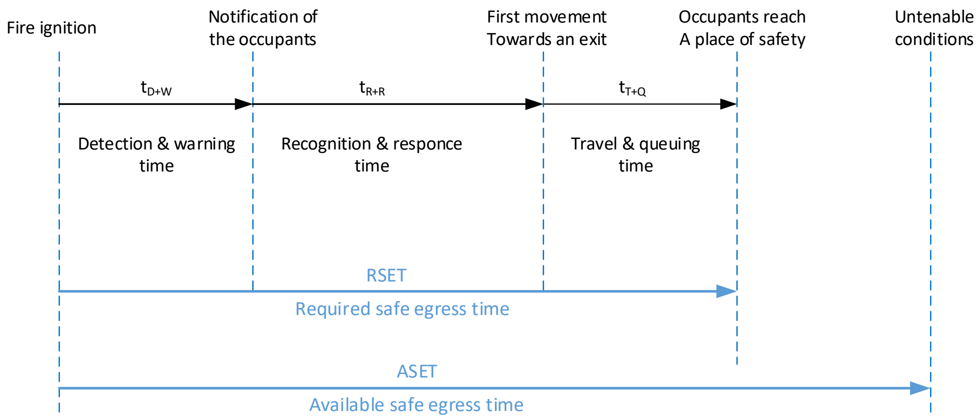

Figure 3 Assessment of RSET vs ASET ratio

The ASET is the result of the actual fire scenariou within a specific building. The available time for rescue is predicted taking into account the timely development of a fire as an important parameter as shown in Figure 7. The development is dependent on the initial materials starting the fire and the other materials near the fire location that may lead to flash over and fire spread. A room will be filled with smoke in a hot layer just below the ceiling. During the fire the hot layer will become thicker and may be the cause for a flash over situation when the heat radiation form this layer is growing above a threshold value. It is typically assumed a value of 20 kW/m^2 in the Danish regulations. Any building fire will furthermore devellope smoke and toxic fire emissions such as carbon monoxide that may spread to other parts of the building through various openings, such as open doors.

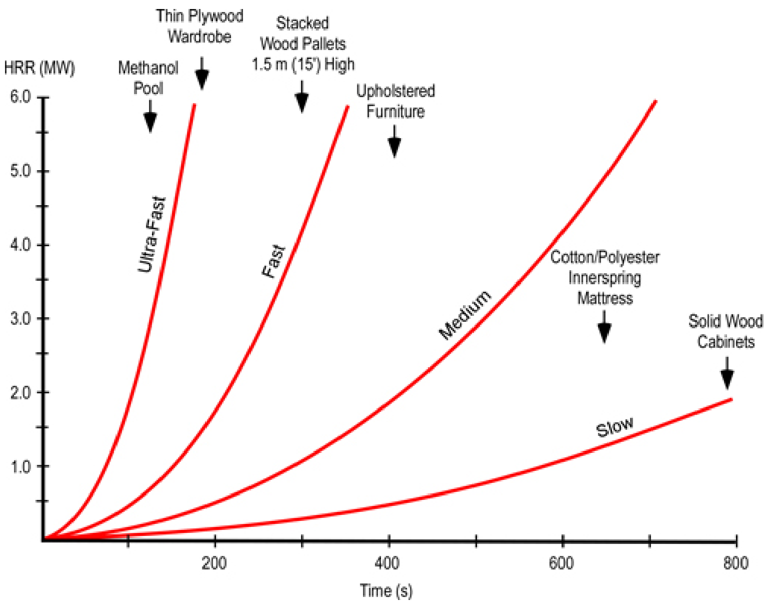

Figure 4 Fire growth rates for different materials: $Q_{HRR} = \propto t^2$.
(http://projects.bre.co.uk/frsdiv/designfires/NFPA.htm)

6. ACCEPTANCE CRITERIA

These fire phenomina mentioned above are described by various parameters as e.g. the tempertaure of hot upper layer, height below the upper layer, concentration of toxic gases and visibility in a room filled with smoke. These paramters are being calculated in the performance based approach and by that certain time profiles for the parameterws are establsihed. In order to predict critical situations e.g. situations where the visibility loss prevents proper evacuation or where the temperature is becomming to heigh for humans to escape a set of threshold criteria are established. The ASET is therefore defined as the time until the first threshold is reached comparing all criteria, i.a. the ASET is defined as the shortest time to reach one of the threshold criteria. These criteria are often reported as tenability or harm criteria to people in the wider literature and these are (see also Figure 9):

- Heat release rate ,
- smoke layer (temperature, toxicity, height);
- visibility;
- heat radiation,
- etc.

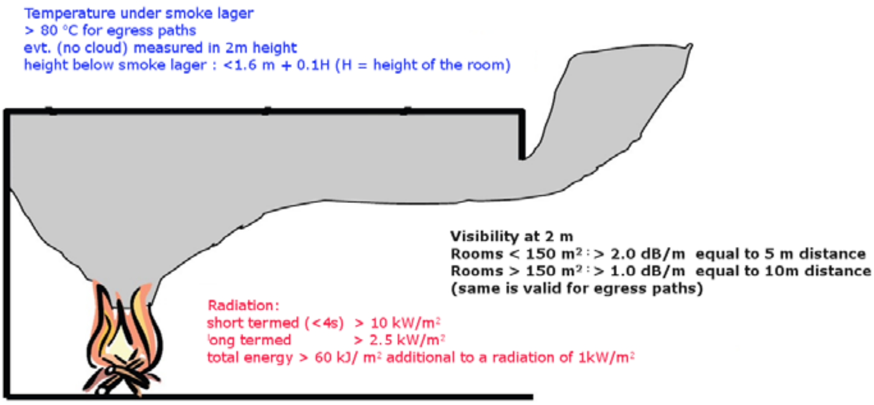

Figure 5 selected harm criteria to people using a performance based fire risk assessment, as established in the Danish guidelines "Information om brandsikkerhed af bygninger" ((The Danish Government 2010)).

By that the ASET is determined and using e.g. evacuation flow models and the former predicted RSET, the number of people at risk may be determined. This is with benefit done using a probabilistic approach as many parameters as the fire loads, the location of the initial fire, the functioning of the fire safety barriers (such as detectors, alarms, fire doors, fire ventialtion, etc.) are of stochastic nature. This may be modelled by probabilistic methods as e.g. Bayesian networks or using event trees (see Figure 13 and fault trees (Figure 14).

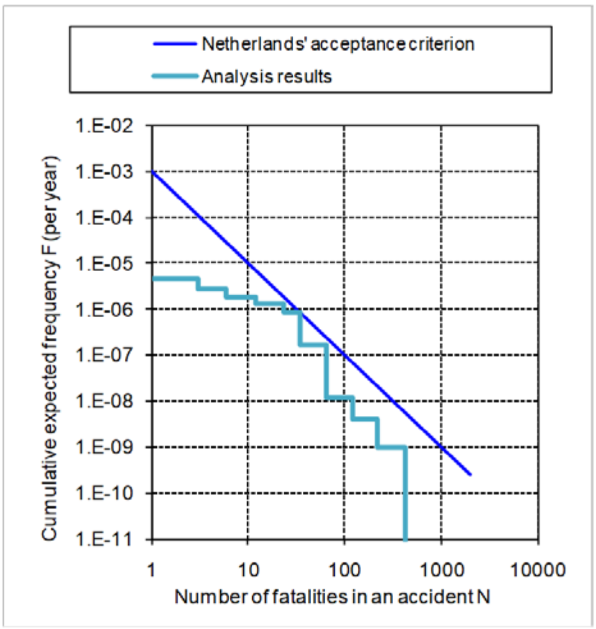

Figure 6 example for FN -curve

A risk based approach will predict an overall probability taking into account the consequences on people, such as lethallity. For the final evaluation of the building or infrastructure safety the risk may be expressed as the individual risk (the risk that an unprotected person at a certain location is lethally affected by the accident. Another measure is the societal risks that includes the population around the accident location. The latter is usually presented in form of FN diagrams (see Figure 8).

7. QUANTITATIVE AND QUALITATIVE FIRE RISK ASSESSMENT

A fire risk assessment is done in several steps as shown in Figure 7. The important very first step is to collect information on the regarded system and to get familiar with it in the systems analysis. The risk assessment afterwards combines qualitative hazard identification and hazard & scenario analysis with deterministic prediction of the consequences and probabilistic description of the likelihood of the different accident scenarious to happen.

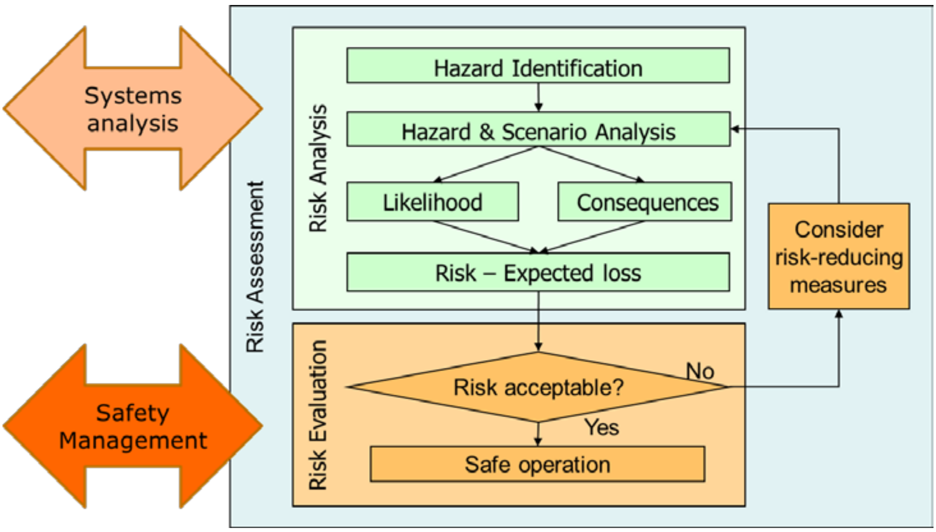

Figure 7 Steps in a fire risk assessment

Based on the likelihood and the consequences, the risk for a specific fire accident may be calculated. The risk is defined as the product of the likelihood of the events times the consequence of the fire scenario.

In order to evaluate the risk, risk accepteance criteria are to be established. The risks and the risk acceptance criteria are compared and when the risks are below the risk acceptance these with the calculated risk leads to decisions on the acceptability of a given scenario.

The results of the risk assessment provides valuable input for safety management strategies in order to establish and maintaine the requested saftey level.

7.1. Hazard identification methods

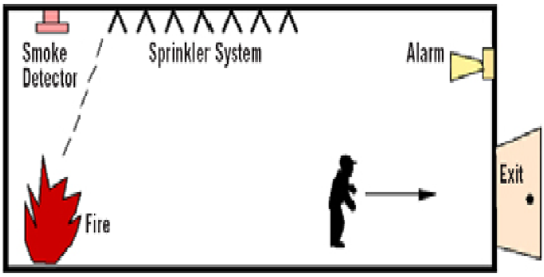

Figure 8 an example fire scenario

In order to predict fire risks the system has to be defined and typical fire scenarios have to be found, as in the example shown in Figure 4. There are numerous qualitative and quantititave methods to assess such scenarious. The application of these may be different as a simple checklist maybe efficient and suitable for standard systems. A HazOP is good to analyse for hazards in flow systems and needs the setup of an expert group that discusses the details of the regarded systems. Similar for FMEA analyses, but the tool is best to find possible hazards on a component level. FTA is excellent to find the root course behind a possible initiating fire event or the reason why e.g. a sprinkler system does not work on demand. The ETA is good to analyse the progress of an initial event (the critical event from the FTA analysis) and predict the out come of e.g. an evacuation scenario taking into account the functioning or malfunctioning of doors and other fire safety installations and proceduree s. The Bow tie analysis is basically a combination of the FTA and the ETA, while the Safety barrier diagrams are an excellent extension of these, as it provides a more simple representation of the scenarious and is focussing on the safety barriers. Some common methods are:

- Checklists – good for well defined systems
- HAZOP - Hazard and Operability Study - good to find hazards in a flow system
- FMEA - Failure Modes and Effects Analysis – good to find hazards by components
- FTA - Fault Tree Analysis – good to analyse for the root cause of failures
- ETA - Event Tree Analysis –good to analyse the progression of events

- Safety Barrier diagrams- good to analyse the appropriateness of safety barriers (see Figure 5)
- Bow-tie- combination of FTA and ETA (see Figure 6 and e.g. (Hakobyan et al. 2008; Salvi & Debray 2006))

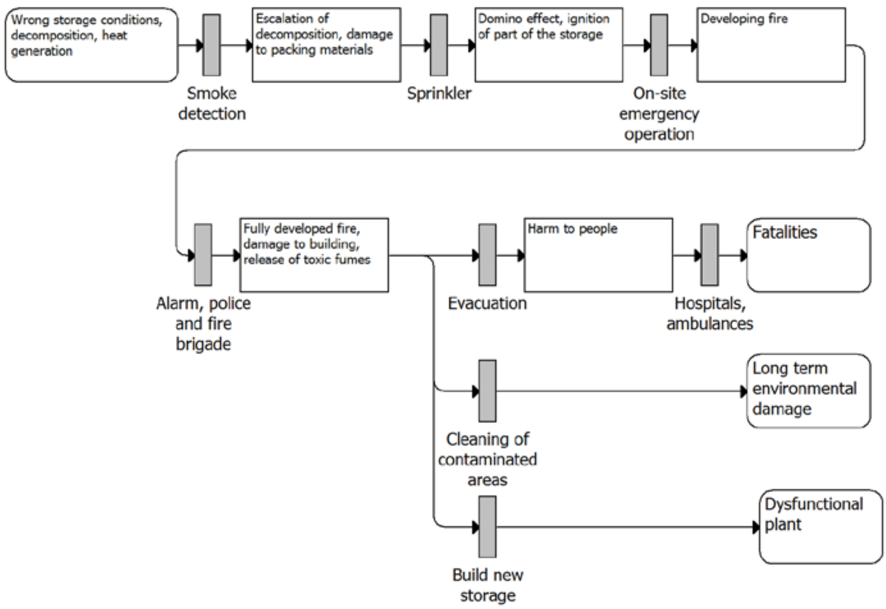

Figure 9 Example for an Safety Barrier diagram for a warehouse fire scenario

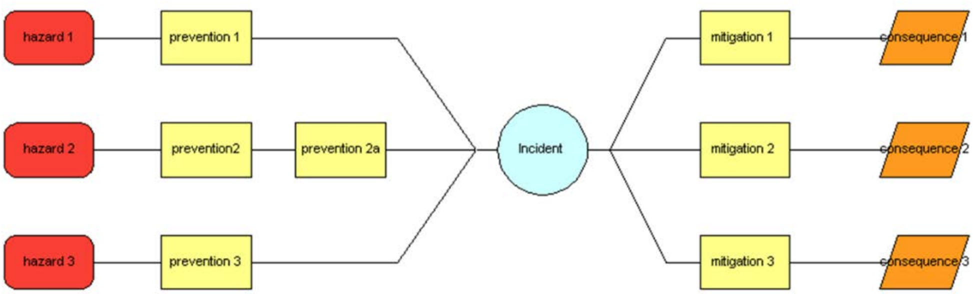

Figure 10 The Bow tie diagramm

7.1.1. Event trees

Event trees ET are very common in fire safety engineering and maybe used to describe found fire scenarious as indicated in Figure 10. A ET (see Figure 13) is modelling the events that are following a starting fire and easily can include working or not working states for detection, alarms, sprinklers and other. It is also possible to include probabilities or frequencies for each event and therefore it is possible to calculate the probability of each resulting scenario.

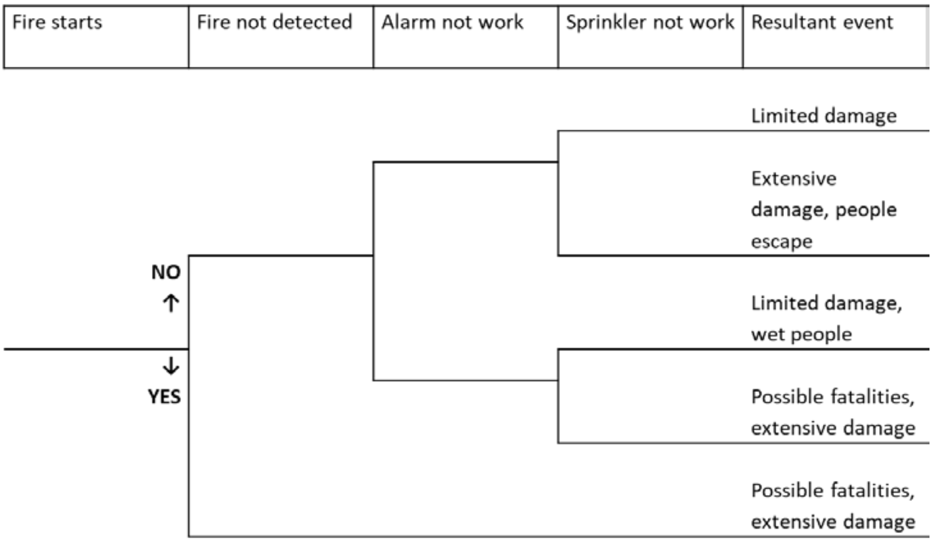

Figure 11 Event tree based on fire scenario defiend in Figure 4

7.1.2.Fault trees

Fault trees FT (see Figure 14) are modelling the causes that may result in the critical event as e.g. “the fire protection system fails”. FT are often used to find root causes of such critical events and therefore are describing and enable to calculate the probability of such events. An FT is broken down in sub causes until the root causes are found. It uses logical AND or OR gates and this enables to calculate the probability of the critical events just knowing the failure frequency of the root causes.

7.1.3. Bayesian Beliefe networks

Probabilistic assessment uses many different methods. The above described ET and FT methods are often used by the frequentists, as the quantification requires statistical data. Another and increasingly popular method is the Bayesian believe networks BBN that may predict a probability of events using the concept of the believe. It is different from the frequentist approach. This concept is subject to another lecture.

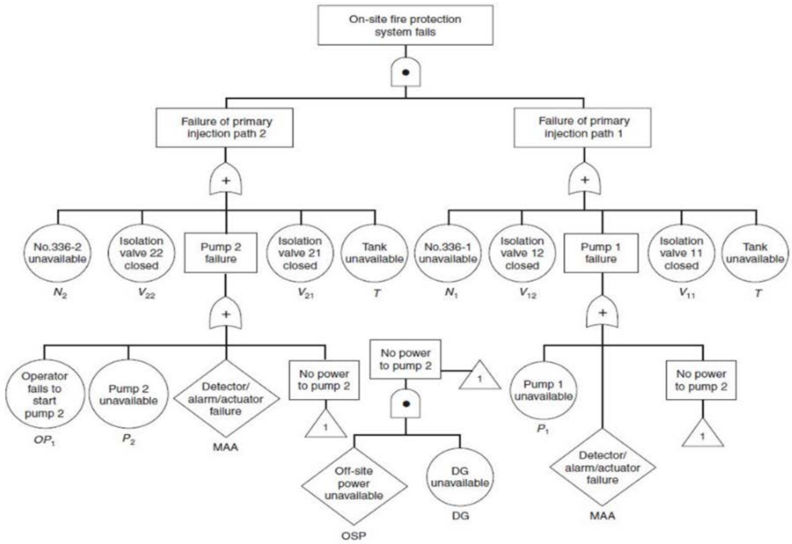

Figure 12 Example of a fault tree of a sprinkler system

8. STATIC VS. DYNAMIC METHODS

The above mentioned models are to be considered as static methods as they do not take into account dynamic changes. These are lumped into average. An introduction of dynamics is difficult, but would be valuable to predict failures and consequences of dynamic interdependent systems (Duijm et al. 2013; Frank Markert et al. 2016; F. Markert et al. 2016). The term "dynamic risk assessment", is interpreted differently ((Hakobyan et al. 2008):

- Methods for periodic updates of an Probabilistic Risk Analysis (PRA) to address any changes in a plant configuration
- Updates to account for the ageing of equipment
- Approaches that include explicit deterministic modelling of dynamic processes combined with stochastic modelling to describe a systems evolution.

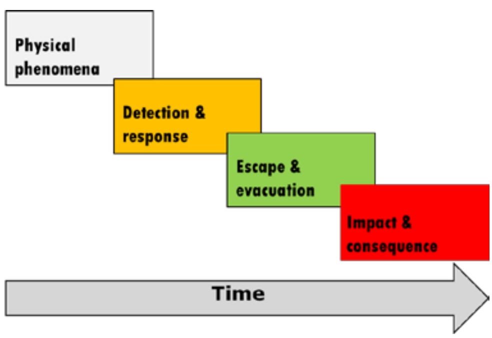

Figure 13 dynamic approach with mutual dependent sub-scenarious

9. UNCERTAINTIES

Any determistic and probabilistic assessment will contain some uncertainties. General speaking these uncertainties can be divided into aleatory and epistemic uncertainties. The aleatory uncertainties are describing the inherent variations associated with a physical system, as e.g. weather parameters at a certain point of time and space. These are unavoidable. The epistemic uncertainties are caused by an incomplete understanding of the system. This may be caused because the system or building is newapplying new nt sufficiently tested materials are combinations of these. As epistemic uncertainty is caused by a lack of knowledge this type of uncertainty may be reduced by increasing the knowledge of teh regarded system. In a real world situation the risk assessments usually will include a combination of aleatory and epistemic uncertainties in the results.

Tabel 1 Uncertainties found in fire modelling

Aleatory uncertainty	**Epistemic uncertainty**
It describes **the inherent variation associated with the physical system or the environment** under consideration.	It derives from some **level of ignorance, or incomplete information** about the system / the surrounding environment.
Other equivalent terms:	
• stochastic uncertainty (variability) • irreducible uncertainty • inherent uncertainty	• subjective uncertainty • reducible uncertainty • model form uncertainty

Real fire risk assessment problems typically embraces both types of uncertainty.

For management purposes accidents are ranked semi quantitaive with help of a tarfic light graph as shown in Figure 14. The accidents with acceptable risk (probaility of occurance times consequence) will be found in the green area , while unaccepatble risk will be shown in the red area. There is defined a yellow area were the technology may be acceptable when the systems provides a risk as low as practical possible ALARP. This principal is used to e.g. decide on further safety barriers and may be comparing the cost for these measures and the costs resulting form the consequences of an accident.

In Figure 15 the traffic light graph is additional indicating areas of uncertainties as investigated by (Renn & Klinke 2004). They found a number of clusters which are detrmined by there uncertainty in the risk both due to the uncertainty on the consequence and the probability that an accident may occur. This is further explained in Table 1 together with three different types of maangement strategies to cope with the different situations.

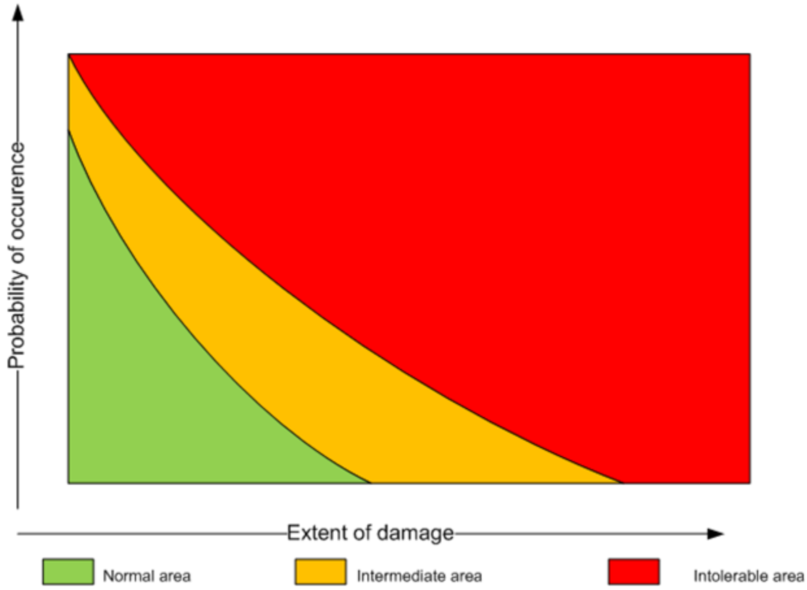

Figure 14 traffic light graph to indicate the acceptability of risks

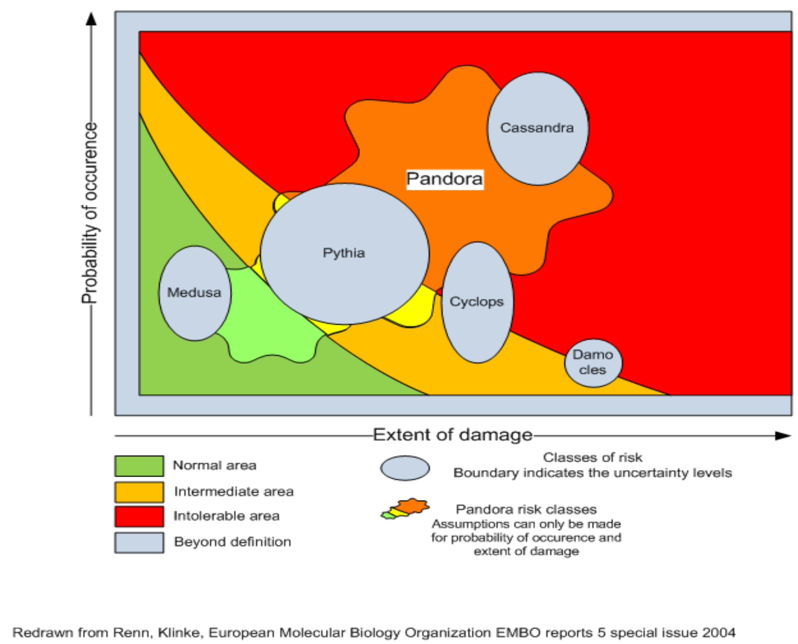

Figure 15 traffic light graph including types of uncertainty after (Renn & Klinke 2004)

Table 1 management strategies in relation to the recognized uncertainties

Management	**Risk class**	**Extent of damage**	**Probability of occurrence**	**Strategies for action**
Science-based	Damocles Cyclops	High High	Low Uncertain	•Reducing disaster potential •Ascertaining probability •Increasing resilience •Preventing surprises •Emergency management
Precautionary	Pythia Pandora	Uncertain Uncertain	Uncertain Uncertain	•Implementing precautionary principle •Developing substitutes •Improving knowledge •Reduction and containment •Emergency management
Discursive	Cassandra Medusa	High Low	High Low	•Consciousness building •Confidence building •Public participation •Risk communication •Contingency management

10. MANAGEMENT STRATEGIES UNDER UNCERTAINTY

Table 1 shows three mangement strategies depending on the uncertainty in the results of the risk assessment. The authors Renn and Klinke suggest an scientifc technical based management approach for situations were the system is well defined and the uncertainties are low or uncertain with respect to the occurance and high on the expected damage resulting from the consequences. For a situation were accidents resulting from a highly needed technology are giving high damage and also are occuring with a high probability, it is suggested to have a discursive management approach in order to have a public participation of the needs for this technology and an appropriate risk communication. Such a discursive management approach is also suggested in case of technologis that fully are acceptable with low damage and low probability of occurance, but where the public still has many doubts on the safety of the technology. In cases of new technologies where the knowledge is immature to estimate the degree of damage and the frequency of occurance a precautionary management approach is suggested.

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